

A joint GMRT/X-ray study of galaxy groups

E. O’Sullivan¹, S. Giacintucci¹, J. M. Vrtillek¹, S. Raychaudhury², R. Athreya³, T. Venturi⁴ and L. P. David¹

¹*Harvard-Smithsonian Center for Astrophysics, USA*

²*University of Birmingham, UK*

³*NCRA-TIFR Pune, India*

⁴*INAF-IRA Bologna, Italy*

Abstract. We present results from combined low-frequency radio and X-ray studies of nearby galaxy groups. We consider two main areas: firstly, the evolutionary process from spiral-dominated, HI-rich groups to elliptical-dominated systems with hot, X-ray emitting gas halos; secondly, the mechanism of AGN feedback which appears to balance radiative cooling of the hot halos of evolved groups. The combination of radio and X-ray observations provides a powerful tool for these studies, allowing examination of gas in both hot and cool phases, and of the effects of shock heating and AGN outbursts. Low-frequency radio data are effective in detecting older and less energetic electron populations and are therefore vital for the determination of the energetics and history of such events. We present results from our ongoing study of Stephan’s Quintet, a spiral-rich group in which tidal interactions and shock heating appear to be transforming HI in the galaxies into a diffuse X-ray emitting halo, and show examples of AGN feedback from our sample of elliptical-dominated groups, where multi-band low-frequency radio data have proved particularly useful.

1. Introduction

Feedback processes play an important role in governing the development and evolution of galaxies and the groups and clusters in which they reside. In galaxy clusters AGN-driven radio sources appear to be the primary means of balancing cooling in the hot X-ray emitting gas halo, and thus preventing high rates of star formation which are not observed. However, the impact of feedback processes may be most important in less massive galaxy groups, where the majority of galaxies – and the majority of baryonic matter in the Universe – reside (Eke et al. 2004). To understand the mechanisms by which feedback operates in groups and the effect of the AGN/hot gas interactions, we have begun a study of a number of nearby systems using high-quality multi-frequency GMRT observations and deep archival Chandra and XMM-Newton X-ray data. Of particular interest are: i) the relationship between the observed X-ray and radio structures, ii) the mechanisms of energy injection, and iii) the properties of the radio galaxies, including their ages and duty cycles.

Galaxy groups are a diverse class of systems, ranging from loosely bound, recently virialised systems to compact formations in which galaxy interactions are common. A broad distinction can be drawn between spiral-rich and elliptical-

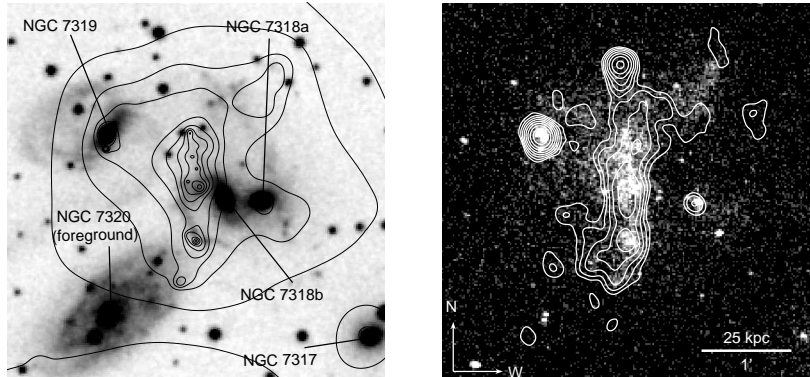


Figure 1. *Left:* Smoothed *Chandra* X-ray contours overlaid on POSS2 B_j -band image of Stephan’s Quintet, with principal galaxies marked. *Right:* GMRT 610 MHz contours overlaid on *Chandra* 0.3–2.0 keV image of the group. Contours are spaced by factors of 2, beginning at $3 \times \text{r.m.s.} = 0.36 \text{ mJy/b}$. The HPBW is $6'' \times 5''$. The panels have identical scale and alignment.

dominated systems: the latter commonly possess an extended halo of hot, X-ray emitting gas, little HI except in galaxies at large radii, and typically have a central FR-I (or more rarely FR-II) radio galaxy. Spiral-rich groups are generally X-ray faint, but contain much larger amounts of HI in the galaxies or in tidal features. The merging process by which spirals in these systems are transformed into ellipticals is relatively well understood, but it is as yet unclear what happens to the cold gas in the galaxies, or how the hot halo is formed. To investigate these issues we have selected a small sample of spiral-rich groups currently undergoing rapid evolution. We discuss results from the first of these below.

2. Stephan’s Quintet

Stephan’s Quintet (HCG 92) is a galaxy group consisting of five main members, of which four are located in a compact core, with one foreground spiral galaxy superimposed (see Fig. 1). The group is a rare example of an ongoing high-velocity galaxy interaction; NGC 7318b, a near-edge-on spiral galaxy, is passing through the group core with a velocity of $\sim 850 \text{ km s}^{-1}$. A ridge of radio continuum emission is observed at 1.4 GHz, coincident with the eastern edge of the galaxy, and this has been interpreted as a shock caused by the collision of NGC 7318b with tidally stripped HI (see Sulentic et al. 2001, for a summary). This feature is observed in several wavebands, most notably in H_α and X-ray (e.g., Trinchieri et al. 2005). The group also shows evidence of past interactions, including stellar and HI tidal tails, thought to have been formed by one or more passages through the group core by a small spiral galaxy, NGC 7320c (Moles et al. 1997, not shown in Fig. 1). The HI with which NGC 7318b is colliding is likely material stripped from the galaxies during these interactions.

We have examined the structure of the ridge and the surrounding diffuse gas using a combination of GMRT 610 and 327 MHz, and VLA 1.4 GHz radio observations and a deep ($\sim 93 \text{ ks}$) *Chandra* pointing (O’Sullivan et al. 2008).

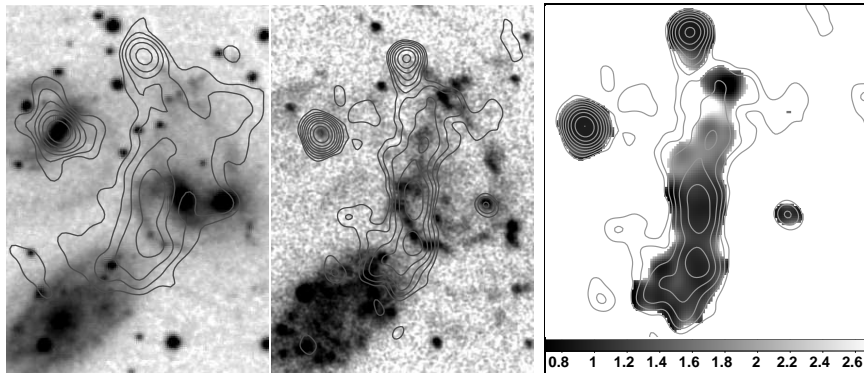


Figure 2. *Left:* 327 MHz GMRT contours overlaid on POSS blue image of the core of Stephan's Quintet. Contours start from $3 \times \text{r.m.s.} = 0.9 \text{ mJy/b}$, HPBW is $12'' \times 10''$. *Center:* 610 MHz GMRT contours overlaid on a *Swift* UVOT UVW2-band image ($\sim 200 \text{ nm}$). *Right:* 1400-610 MHz spectral index map (HPBW of $6'' \times 5''$) with 610 MHz contours overlaid.

Fig. 1 shows the location and structure of the ridge, and a comparison of the relative structures in radio and X-ray bands. The X-ray emission is brightest in the northern part of the ridge, while the radio emission is brightest in the south. Fig. 2 shows GMRT 327 and 610 MHz contours overlaid on optical and UV images of the group core, and on a 1400-610 MHz spectral index map. The diffuse radio emission is more extended at lower frequencies, including areas west of the ridge and emphasizing the brightness of the southern part of the ridge. The spectral index map shows similar structure; the southern part of the ridge has an index of 0.7-0.8, while the northern part has a steeper spectrum. The brightest radio emission corresponds with knots of UV emission in the south-eastern spiral arm of NGC 7318b and as the spectral index in this region is consistent with star formation it seems likely that the underlying extended radio emission arising from shocks is enhanced by star formation in some areas.

From the large-scale diffuse X-ray emission, we can estimate the extent of the gas halo ($\sim 80 \text{ kpc}$) and its total mass, $\sim 2.8 \times 10^{10} M_{\odot}$. This is similar to the estimated HI deficit of the group ($\sim 2 \times 10^{10} M_{\odot}$, Verdes-Montenegro et al. 2001), suggesting that the majority of the hot gas in the system may have been formed by shock heating HI. However, the time taken for such gas to expand at the sound speed from the region of the ridge ($\sim 125 \text{ Myr}$) is much longer than the total time for NGC 7318b to pass through the group (20-80 Myr Sulentic et al. 2001). It therefore seems likely that multiple episodes of shock heating are necessary. The prior interactions with NGC 7320c could be responsible.

3. AGN feedback in elliptical-dominated groups

we have also assembled a sample of 18 X-ray bright elliptical-dominated groups in order to examine the mechanisms and effects of AGN feedback in such systems. While this is still a work in progress, several systems demonstrate the benefits of our combined approach. In NGC 4636, *Chandra* and *XMM-Newton* observations have revealed a complex of shocks and cavities in the galaxy core

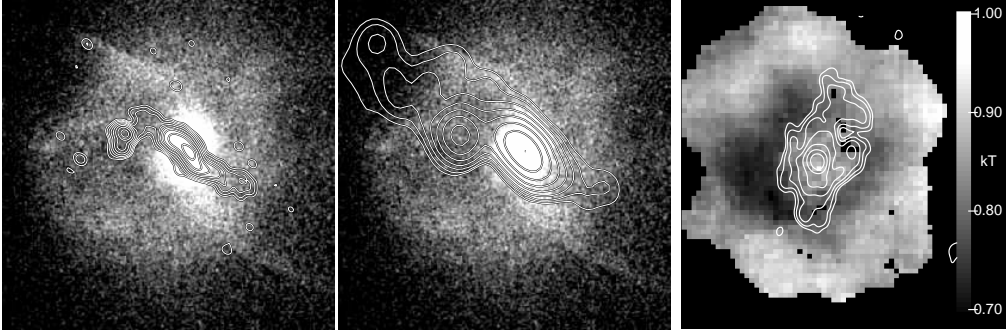


Figure 3. *Left:* GMRT 610 MHz contours overlaid on *Chandra* 0.5–3.0 keV image of NGC 4636. Contours start at $3 \times \text{r.m.s.} = 0.15$ mJy/b, HPBW is $6'' \times 4''$. *Centre:* GMRT 235 MHz contours on the *Chandra* image, $3 \times \text{r.m.s.} = 0.6$ mJy/b, HPBW $16'' \times 13''$. *Right:* *XMM-Newton* X-ray temperature map of the core of the NGC 3411 group (in units of keV) with GMRT 610 MHz contours overlaid. $3 \times \text{r.m.s.} = 0.39$ mJy/b, HPBW $18'' \times 15''$.

(O’Sullivan et al. 2005, and references therein), but VLA 1.4 GHz observations detect only small-scale jets (Allen et al. 2006). Our GMRT 610 and 235 MHz observations (Fig. 3) reveal more extended emission which correlates well with the X-ray structure. This suggests that the AGN of NGC 4636 is restarting, with young jets pushing out into old lobes/cavities from a previous outburst.

NGC 507 provides an example of an old source where no new activity has yet begun. No evidence of jets is found at any frequency, suggesting that the AGN is currently inactive, with the lobes passively aging. Modelling of the radio spectrum (Murgia et al. 2009) supports this picture and indicates that the source has likely been in this ‘dying’ phase for $\sim 30\%$ of its total lifespan. However, X-ray/radio interactions are still playing an important role; without the surrounding hot IGM, the lobes would likely have expanded and diffused, reducing their surface brightness and preventing their detection.

A few systems in the sample show examples of interactions which do not follow the common jet/cavity mechanism. In the NGC 3411 group, X-ray temperature maps reveal a hot core region surrounded by a cool shell of gas, strongly suggesting that an AGN outburst has heated the inner group halo (O’Sullivan et al. 2007). VLA 1.4 and 5 GHz maps show no evidence of jets and very little extended emission, but GMRT observations reveal a much larger scale structure which correlates closely with the heated region (see Fig. 3). The lack of clearly defined lobes and jets could be explained if the lobes were aligned along the line of sight, but this would produce a central X-ray surface brightness deficit, which is not observed. X-ray spectral fitting finds no evidence for a significant inverse-Compton component. It therefore seems likely that AGN heating has occurred through a different mechanism, perhaps involving the disruption of the jets on very small scales, leading to mixing of radio and X-ray plasma in the group core. Further observations are required to test this hypothesis, but if accurate, this would provide a new means to reheat cooling gas in the centres of groups without causing strong disturbances.

4. Conclusions

The results presented here demonstrate the power of combining low-frequency radio and X-ray observations to examine AGN feedback, shock heating and star-formation in galaxy groups. In Stephan's Quintet we may have an example of the type of interactions through which the hot halos of elliptical-dominated groups are built up. The correspondence between the mass of hot gas in the system and the HI deficit suggests that the hot halos of groups may initially form from cool material. The extensive shock heating caused by the collision between NGC 7318b and the HI filament provides a clear mechanism by which this may happen; tidal interactions strip HI from the galaxies and the resulting intergalactic clouds are heated by shocks associated with galaxy merger or capture events. Studies of similar systems should help determine the importance of this mechanism to group evolution.

Examples from our sample of 18 elliptical-dominated groups show the benefits of extending observations to lower frequencies. As well as allowing us to detect faint extended radio structures which go unseen at higher frequencies, radio spectral fitting provides estimates of the age of sources and the state of the plasma in various regions; 'dying' galaxies in which nuclear activity has ceased can be identified, while in restarting sources remnant emission from prior outbursts can be separated from those regions powered by the new jets. This helps us to understand both the mechanisms of AGN feedback and the energies and timescales involved. Such information is key to determining the thermal history of individual systems, and of fundamental importance to our understanding of the role of AGN in galaxy and group evolution.

Acknowledgments. The authors thank D. J. Saikia and S. Immler for providing access to the GMRT and Swift data for Stephan's Quintet. Support for this work was provided by NASA through Chandra Award G07-8133X-R.

References

- Allen, S., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., Reynolds, C. S. 2006, MNRAS, 372, 21
- Eke, V. R., et al. 2004, MNRAS, 348, 866
- Moles, M., Sulentic, J. W., & Marquez, I. 1997, ApJ, 485, L69
- Murgia, M., Parma, P., Mack, K.-H., de Ruiter, H. R., Fanti, R., Markevitch, M., Govoni, F. & Tarchi, A. 2009, A&A, submitted
- O'Sullivan, E., Vrtilak, J. M. & Kempner, J. C. 2005, ApJ, 624, L77
- O'Sullivan, E., Vrtilak, J. M., Harris, D. E. & Ponman, T. J. 2007, ApJ, 658, 299
- O'Sullivan, E., Giacintucci, S., Vrtilak, J. M., Raychaudhury, S. & David, L. P. 2008, arXiv:0812.0383
- Sulentic, J. W., Rosado, M., Dultzin-Hacyan, D., Verdes-Montenegro, L., Trinchieri, G., Xu, C., & Pietsch, W. 2001, AJ, 122, 2993
- Trinchieri, G., Sulentic, J., Pietsch, W., & Breitschwerdt, D. 2005, A&A, 444, 697
- Verdes-Montenegro, L., Yun, M. S., Williams, B. A., Huchtmeier, W. K., Del Olmo, A., & Perea, J. 2001, A&A, 377, 812